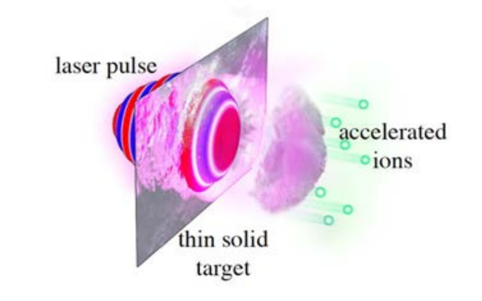
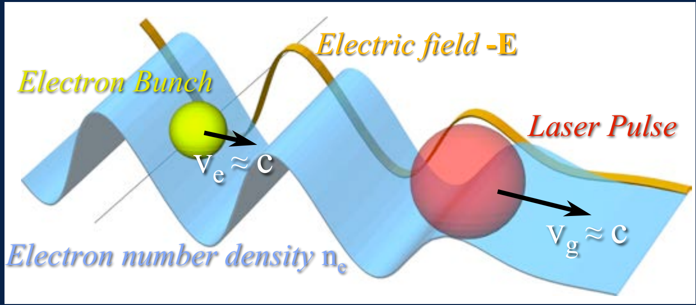
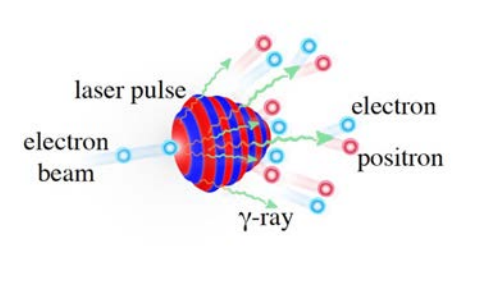
High Energy Density Physics (HEDP)
Short-Pulse Driven Relativistic Plasmas







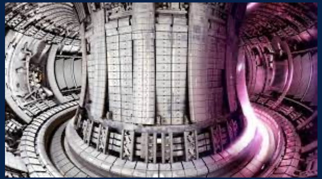
Assistant Professor Louise Willingale (she/her)

COLLEGE OF ENGINEERING
ELECTRICAL & COMPUTER ENGINEERING
UNIVERSITY OF MICHIGAN

SULI 2021, 25th June 2021

My plasma physics journey

Field trip to JET ~2002



Imperial College London

2003 Physics MSci

2007 Plasma Physics PhD

Vulcan laser, UK

M | CUOS THE GÉRARD MOUROU CENTER FOR ULTRAFAST OPTICAL SCIENCE UNIVERSITY OF MICHIGAN

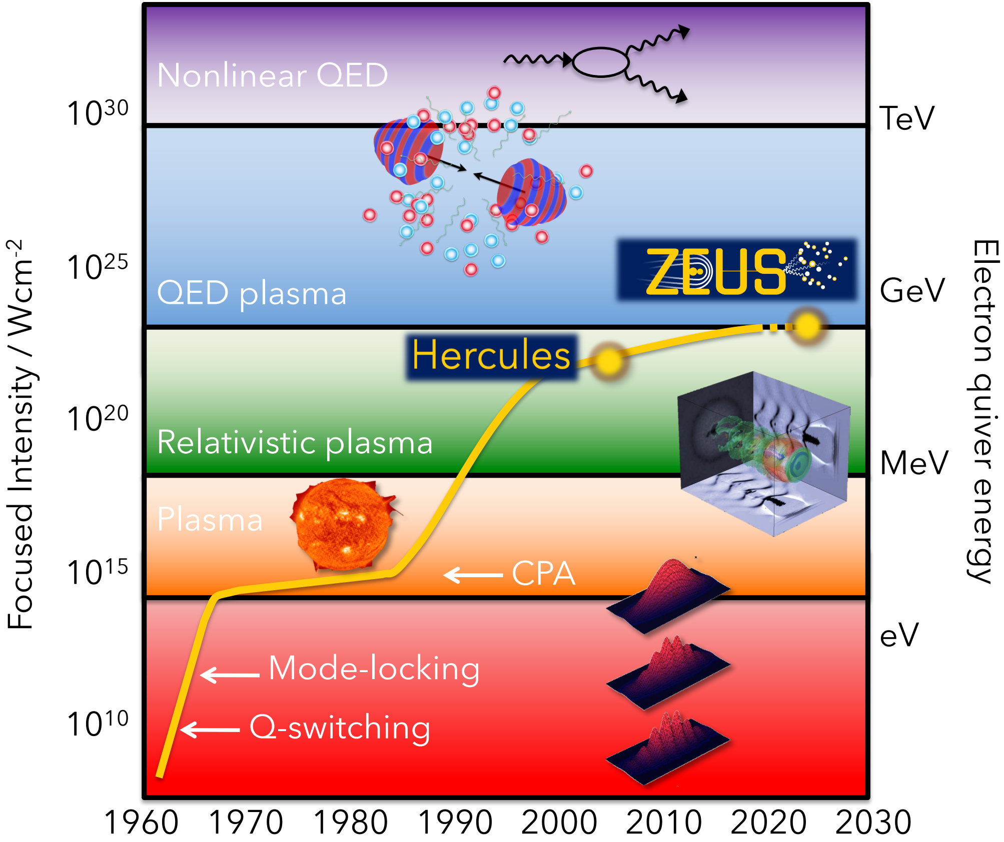
2008 – 2011: Postdoc

2011 – 2014: Assistant Research Scientist

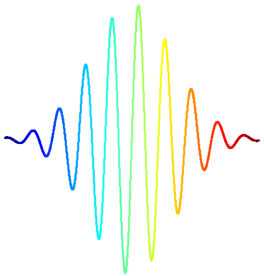
2014 – : Assistant Professor

ZEUS

Creating HEDP conditions: Laser pulses



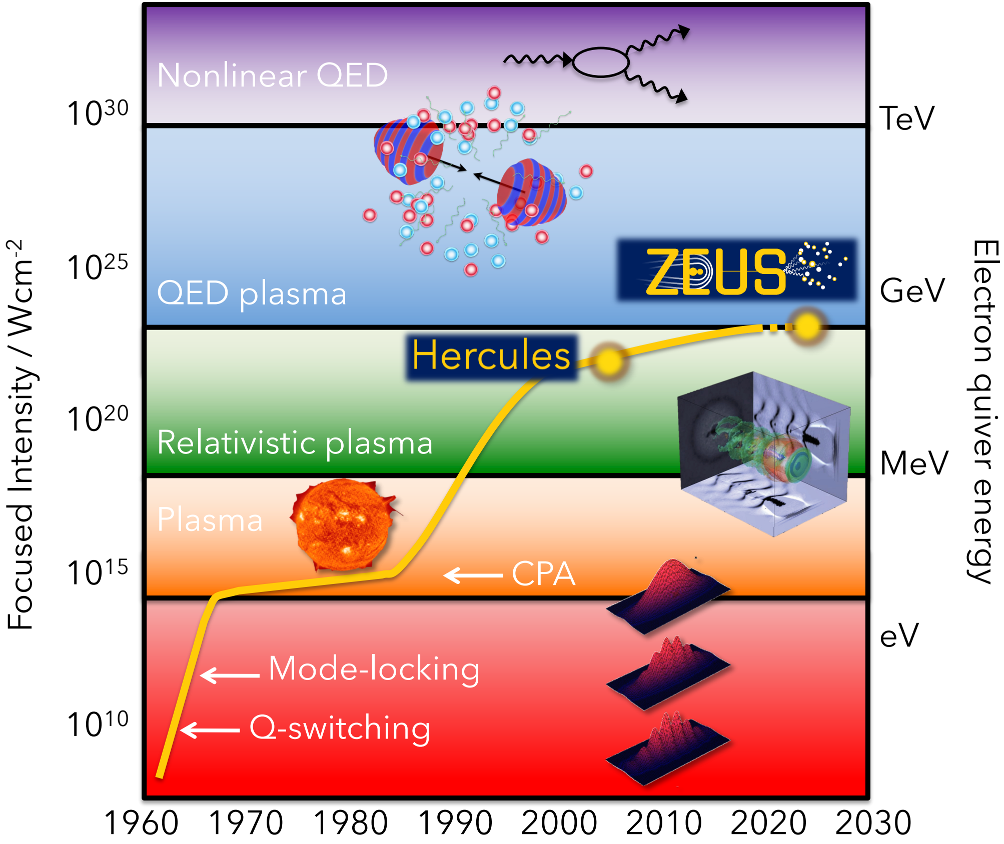
$$Intensity = \frac{Power}{Area} = \frac{Energy}{Time \times Area}$$



For high-intensity, need:

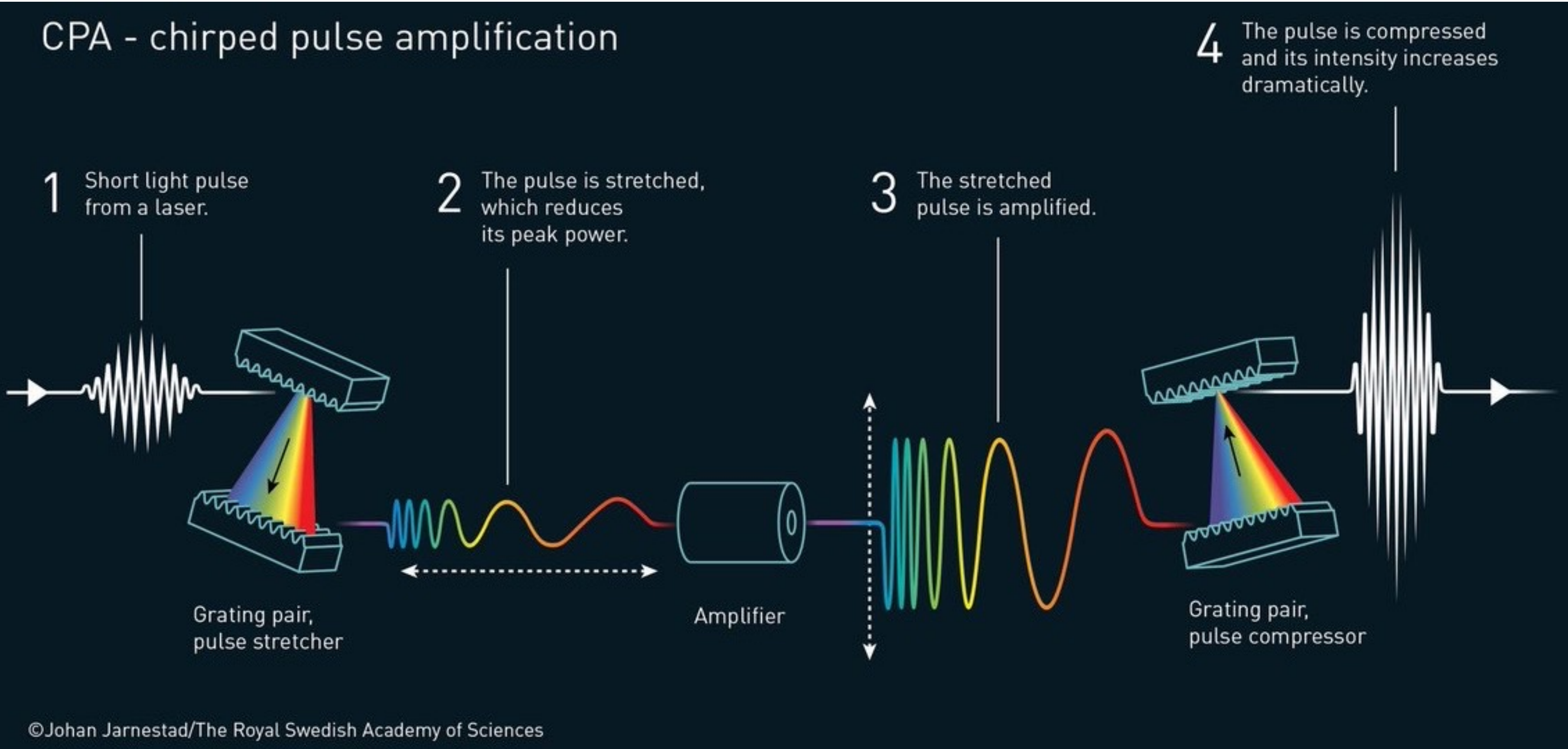
- High Energy
- Short Time
- Small Area

Creating HEDP conditions: Laser pulses



2018 Nobel prize for Physics awarded for CPA development

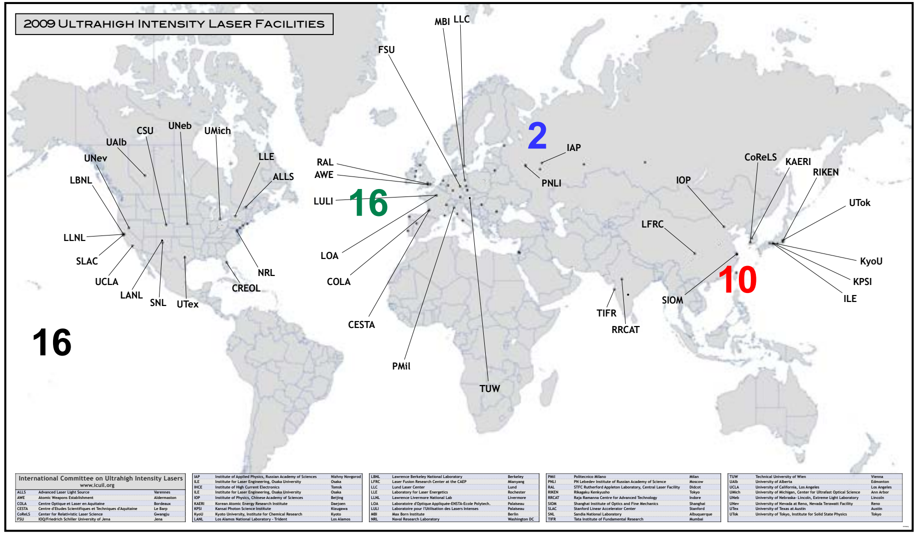
Chirped Pulse Amplification (CPA)



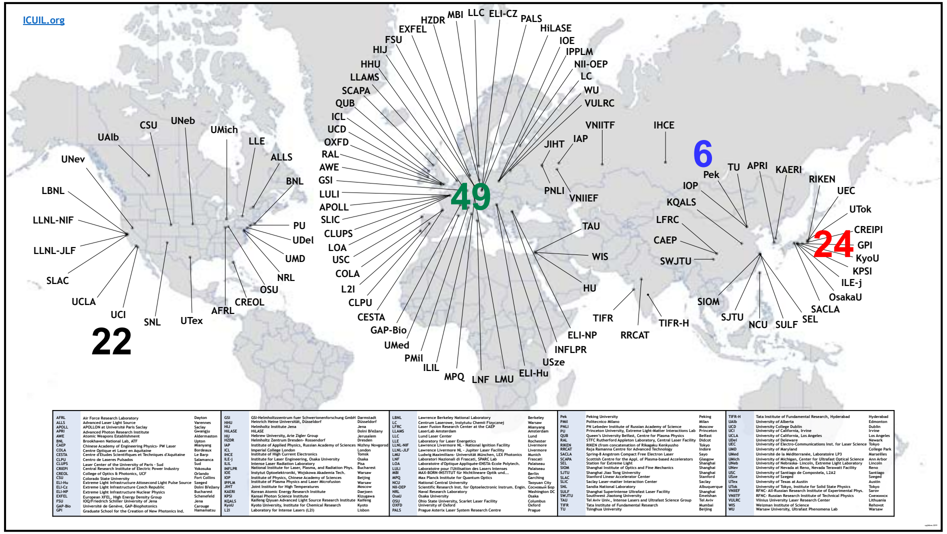
Creating HEDP conditions: Laser pulses

High-peak-power laser facilities world-wide

2009

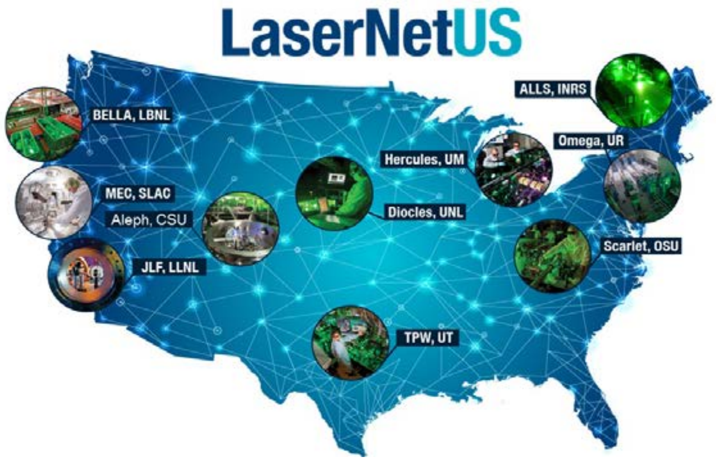


2019

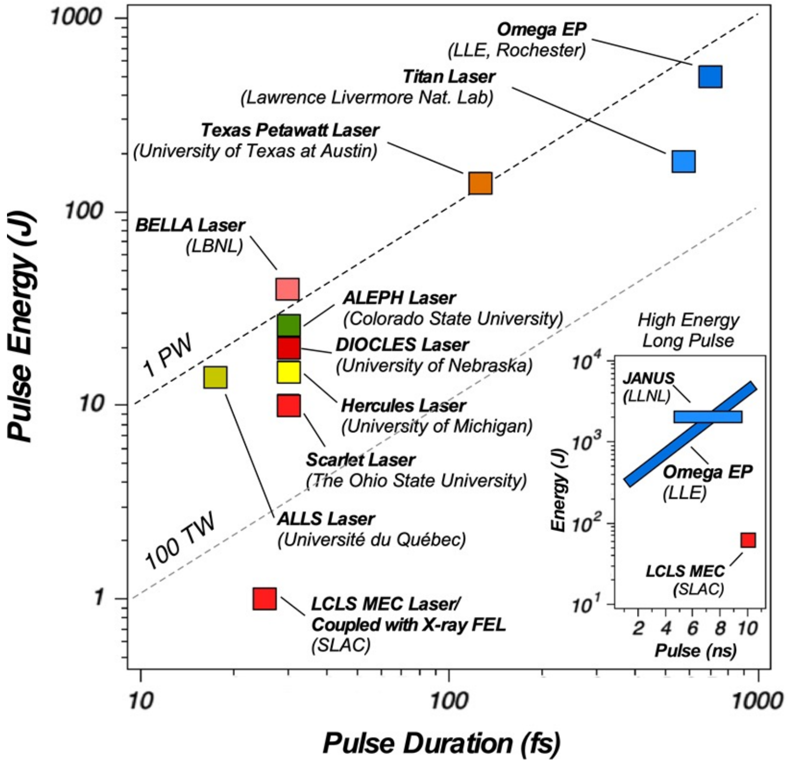


International Committee on Ultra-High Intensity Lasers (ICUIL), https://www.icuil.org/activities/laser-labs.html)

LaserNetUS: Leading facilities span high impact laser regimes



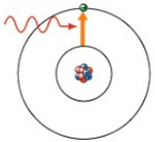
- **10** high power laser facilities
- Includes the **6** most powerful lasers housed at Universities
- Highest powers exceed **1 petawatt**
- Dedicated to the proposition that **ALL** research groups should have access to the brightest light



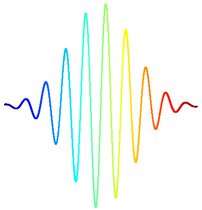
U.S. DEPARTMENT OF ENERGY | Office of Science

Time scales

Atomic processes

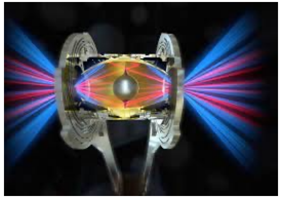


30 fs
Ti:Sapph
CPA lasers

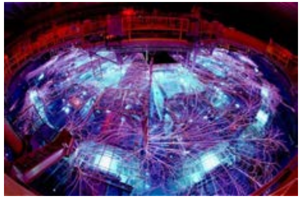


~ 1 ps
Nd:glass
CPA lasers

20 ns
NIF,
OMEGA



< 100 ns
Z-pinch
currents



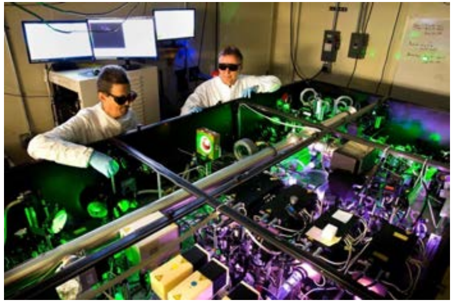
attosecond	femtosecond	picosecond	nanosecond
as	fs	ps	ns
10^{-18} s	10^{-15} s	10^{-12} s	10^{-9} s

Laser intensity

very simplistic calculations...

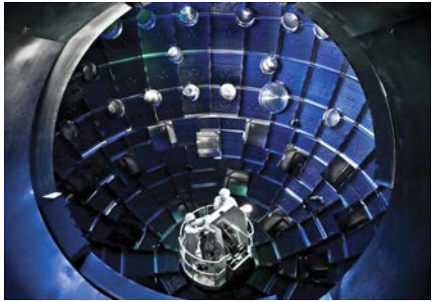
$$\boxed{I = \frac{E_L}{\tau_L \pi r^2}}$$

Hercules



Omega EP

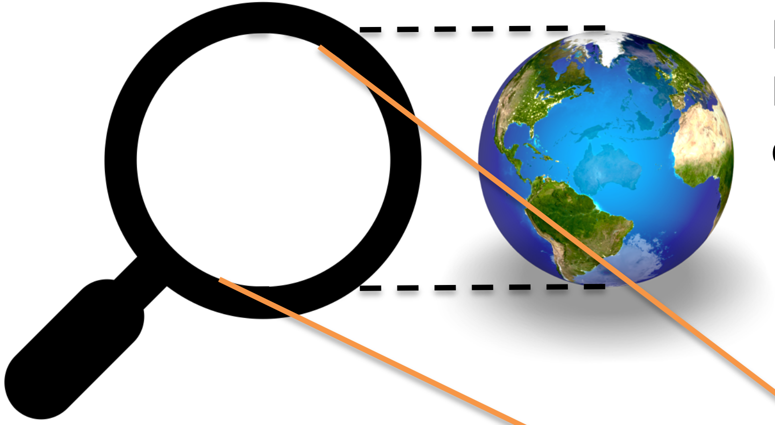
NIF



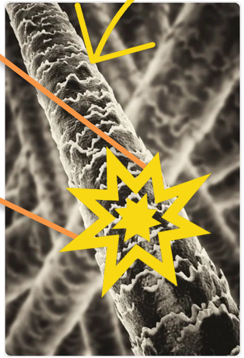
(Per beam)	Hercules	Omega EP	NIF
Energy, E_L	15 J	500 J	5000 J
Pulse duration, τ_L	30 fs	1 ps	~10 ns
Focal spot radius, r	1 µm	10 µm	0.5 mm
Intensity	10^{22} Wcm^{-2}	10^{20} Wcm^{-2}	10^{14} Wcm^{-2}

Laser intensity: 10^{21} Wcm^{-2}

Solar intensity at Earth surface $\approx 1.4\times10^{-4}$ Wcm^{-2}



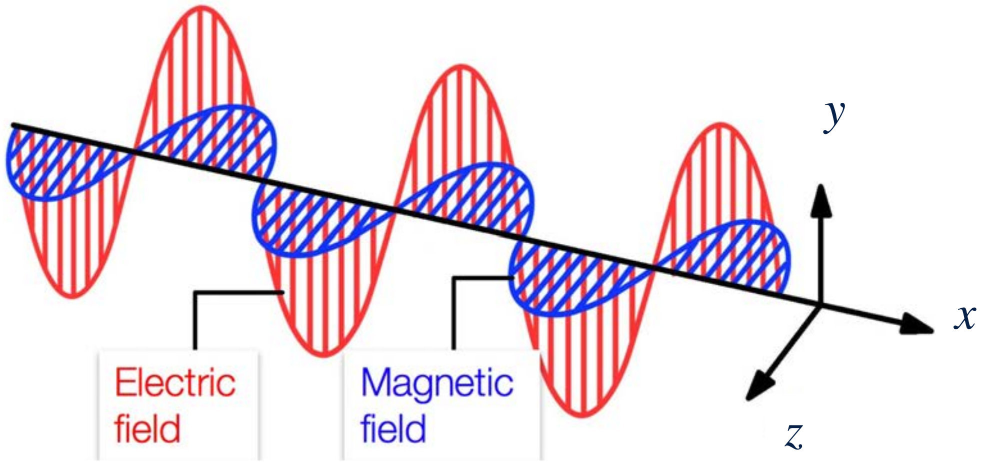
Earth diameter = 6371 km
Power of sun on Earth = 180 TW
c.f. US grid capacity = 1.12 TW



Intensity $\approx 10^{21}$ Wcm^{-2}

Human hair radius ≈ 25 µm

Laser electromagnetic fields



$$\underline{A} = \underline{A}_0 \sin\left(k_L x - \omega_L t\right)$$

$$\boxed{\underline{E} = \frac{\partial \underline{A}}{\partial t} = E_0 \cos\left(k_L x - \omega_L t\right)\hat{\underline{y}}}$$

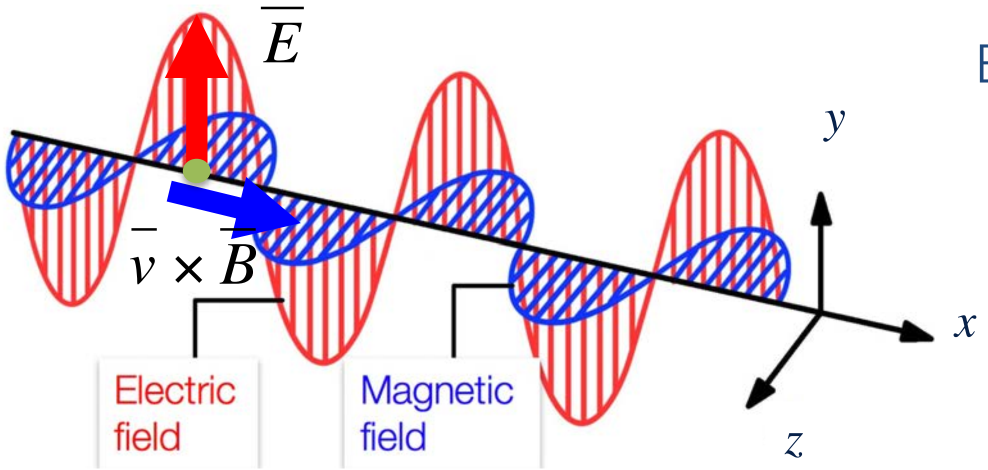
$$\boxed{\underline{B} = \nabla \times \underline{A} = B_0 \cos\left(k_L x - \omega_L t\right)\hat{\underline{z}}}$$

Normalized vector potential (or Classical nonlinearity parameter):

$$\boxed{a = \frac{eA}{m_e c} = \frac{eE\lambda}{2\pi m_e c^2} = \frac{Quiver\ energy\ of\ electron}{m_e c^2}}$$

For $a > 1$, we can generate a relativistic plasma

Motion of an electron in the laser fields



Relativistic regime
a > 1

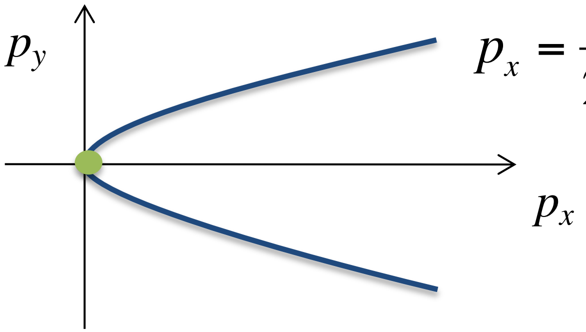
$$I = \frac{a_0^2}{\lambda_\mu^2[\mu m]} 1.4 \times 10^{18}\, W cm^{-2}$$

Electron motion in the laser fields:

$$\frac{d\overline{p}_e}{dt} = -e\left(\overline{E} + \overline{v} \times \overline{B}\right)$$

$v \rightarrow c$

$$\frac{p_y}{m_e c} = a = \frac{eE}{m_e c \omega_L}$$

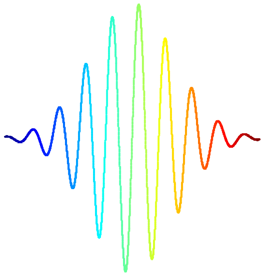


$$p_x = \frac{1}{2} p_y^2$$

$$\frac{p_x}{m_e c} = \frac{a^2}{2}$$

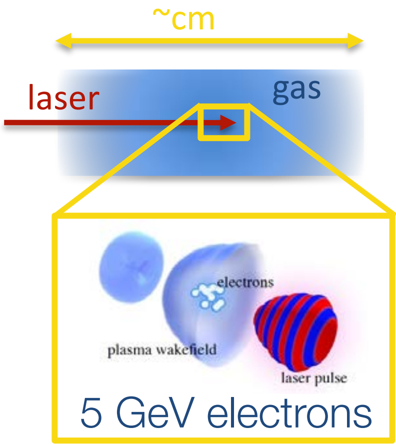
Why study high intensity laser-plasma interactions?

Light pulse



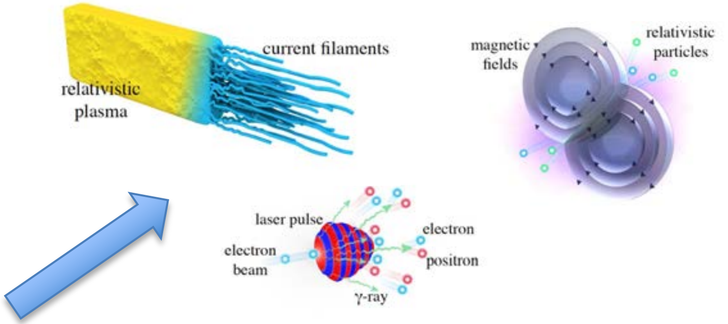
Our "Tool"

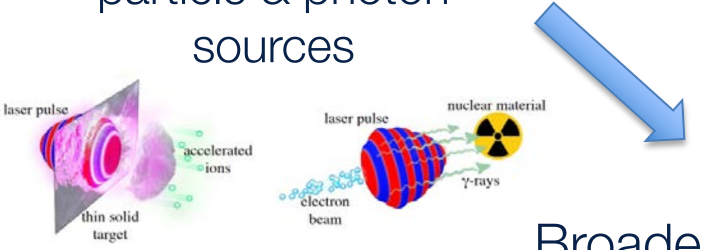
Miniaturize accelerators



Unique, ultrashort, extremely bright particle & photon sources

Probing basic plasma physics

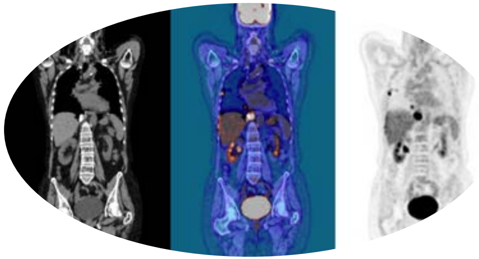




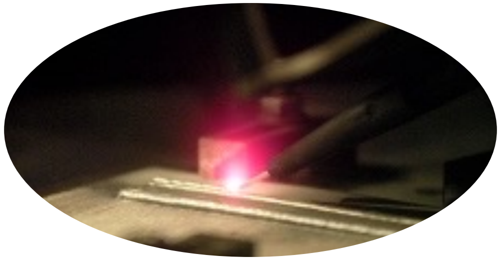
Broader applications…

Applications for particle and light sources

Medicine

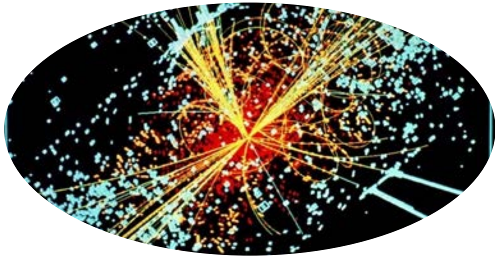


Industry

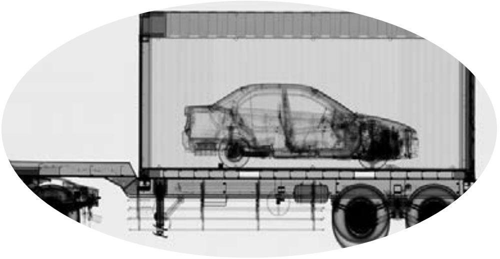


Energy and environment

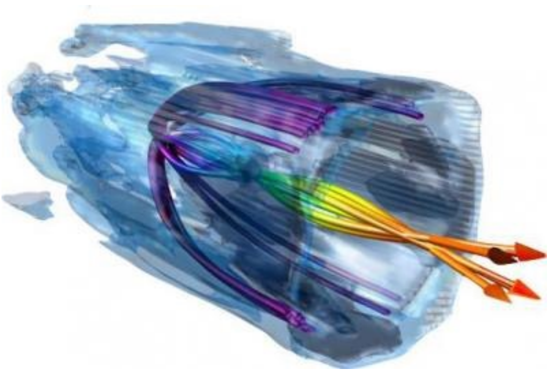
Discovery science



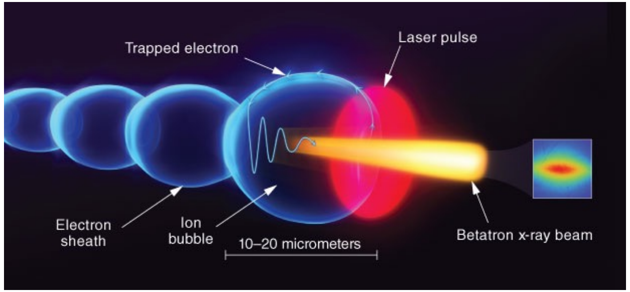
National security



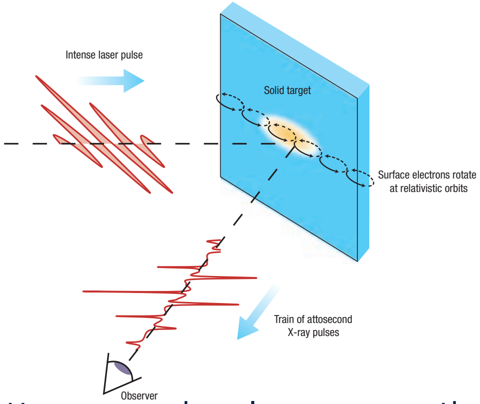
Radiation from high intensity laser-plasma interactions



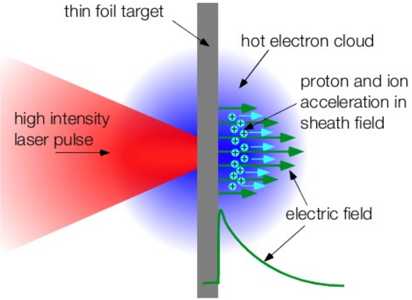
Electron beam generation



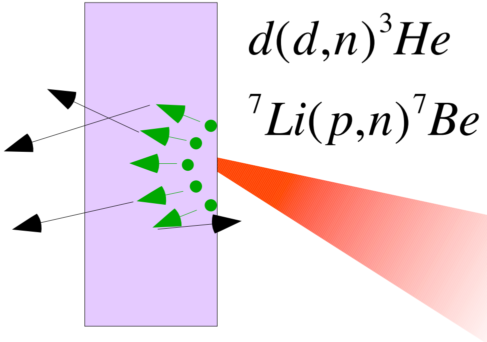
Bright high-energy photon sources



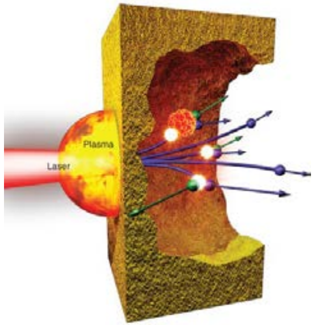
Attosecond pulse generation



Ion beam generation



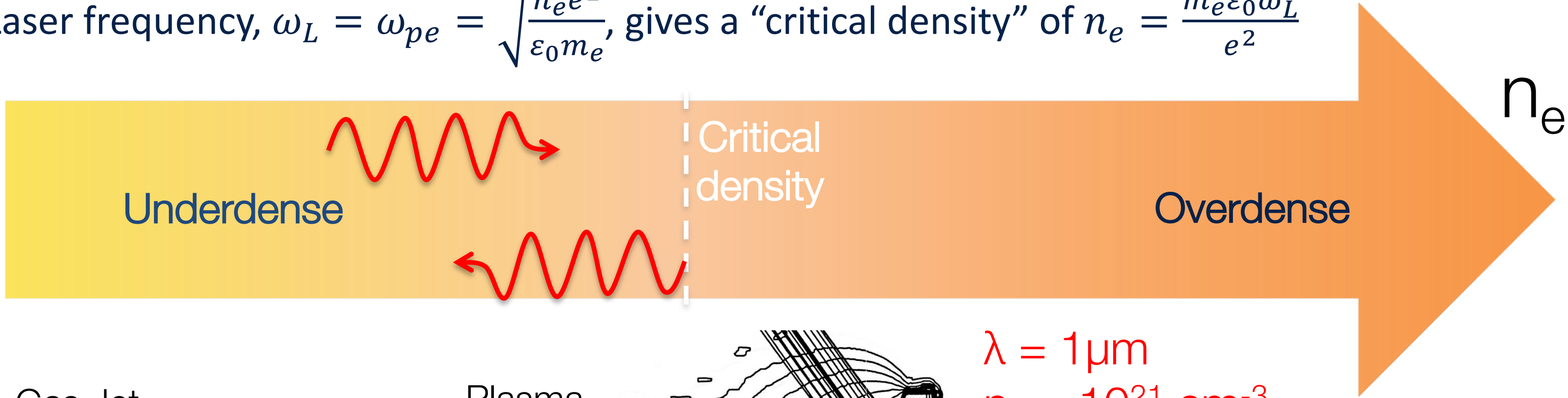
Neutron beam generation



Positron production

Target plasma densities

Laser frequency, $\omega_L = \omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$, gives a "critical density" of $n_e = \frac{m_e \varepsilon_0 \omega_L^2}{e^2}$

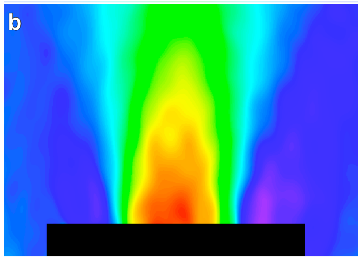


$\lambda = 1\mu m$

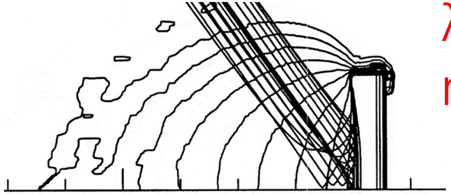
$n_c = 10^{21}\ cm^{-3}$

Gas Jet

$10^{18} - 10^{20}\ cm^{-3}$

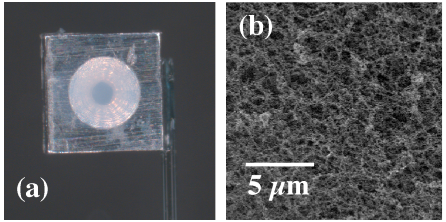


Plasma plume

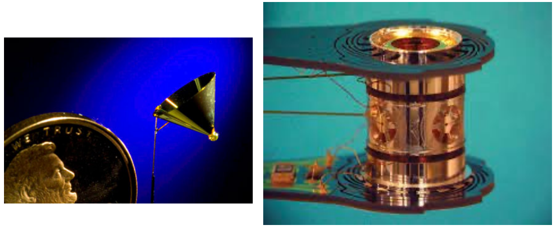


Foam

$0.9 - 30 \times 10^{21}\ cm^{-3}$



Solid foil ~ $10^{24}\ cm^{-3}$



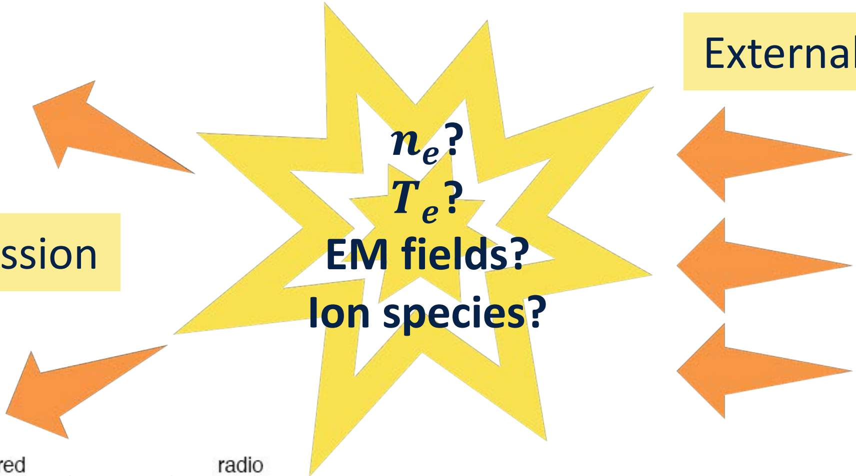
Diagnosing plasma physics: probing

Dr Merritt: “One of the biggest challenges of HED science is to make and measure a high energy system in a lab” → Diagnostics must be very fast

Particles

- Electrons
- Protons
- Ions
- Neutrons
- Positrons

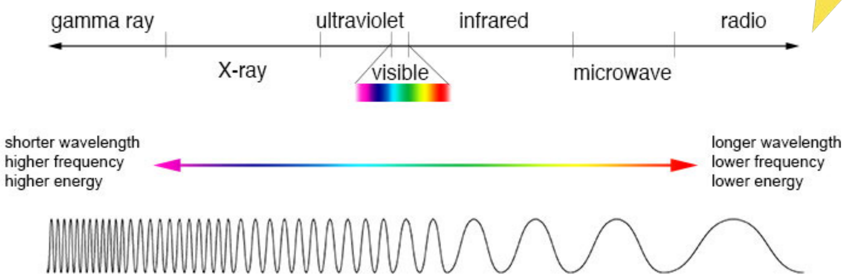
Emission



External probe

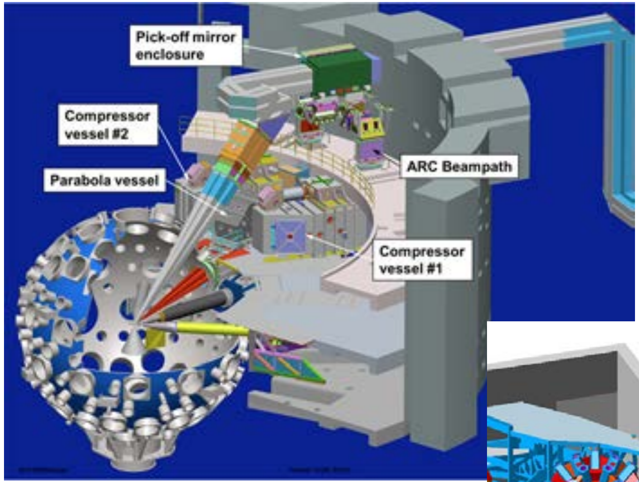
- Optical (laser)
- X-rays
- Particle beam

Photons

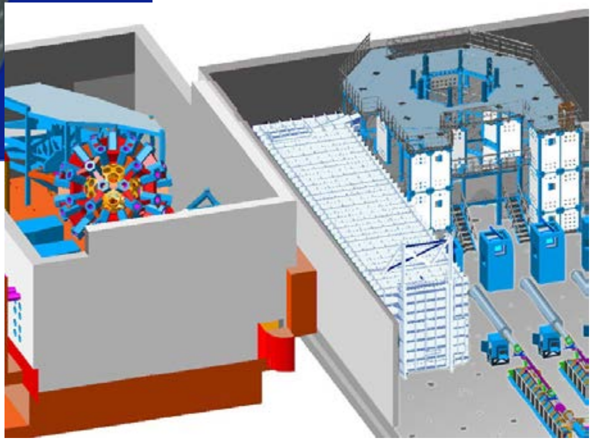


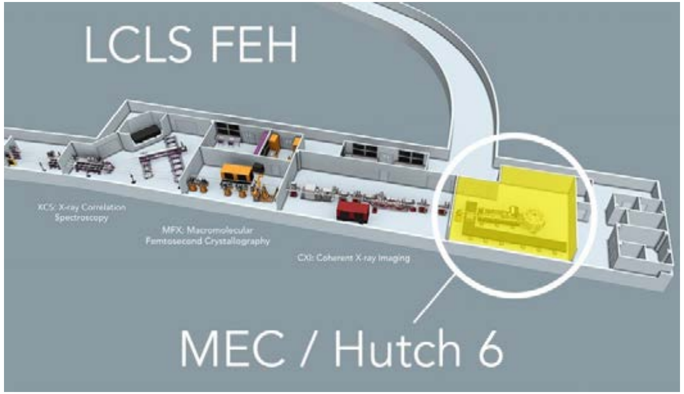
Diagnosing HED plasmas

NIF Advanced Radiographic Capability (ARC)

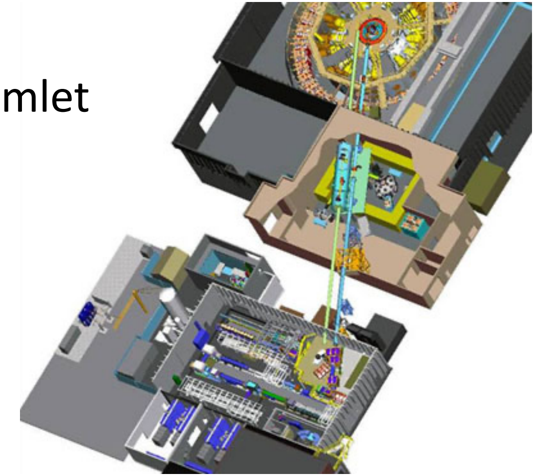


OMEGA EP

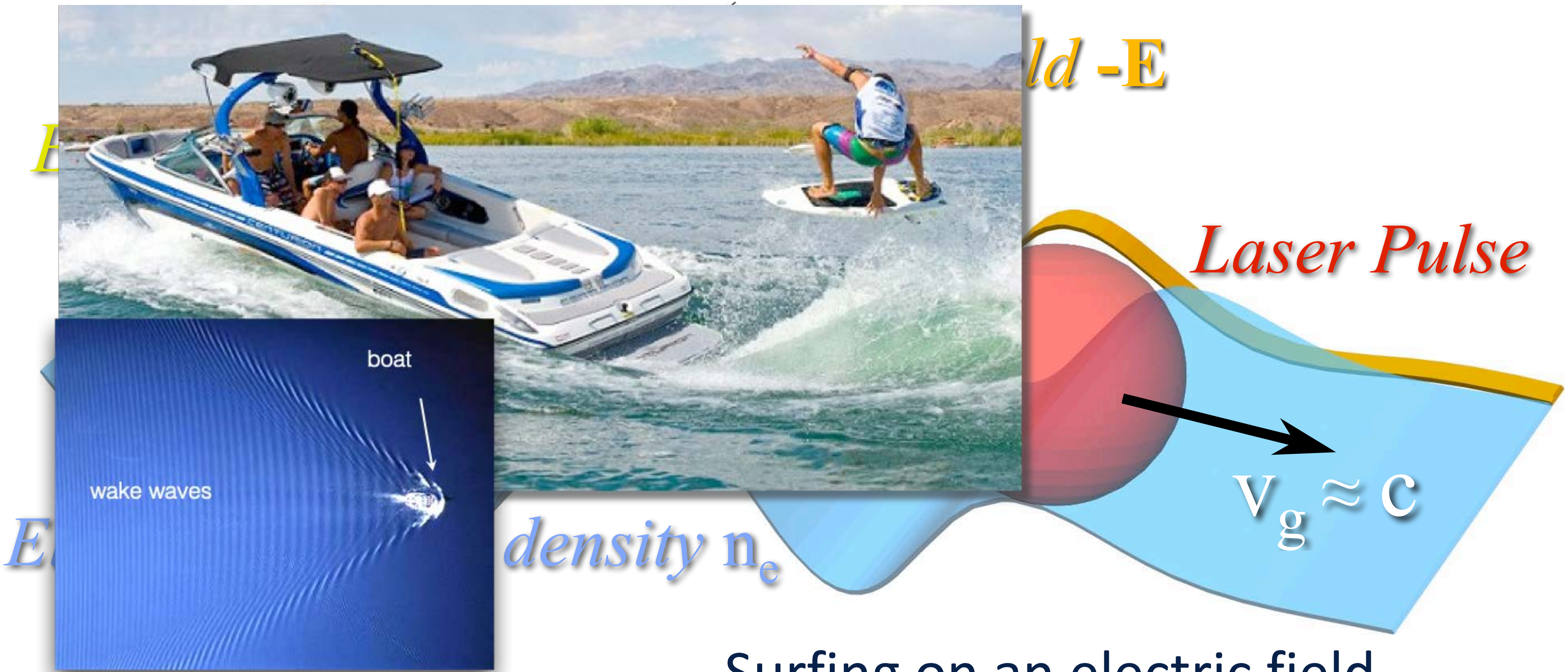




Z-Beamlet



Laser Wakefield Acceleration (LWFA)

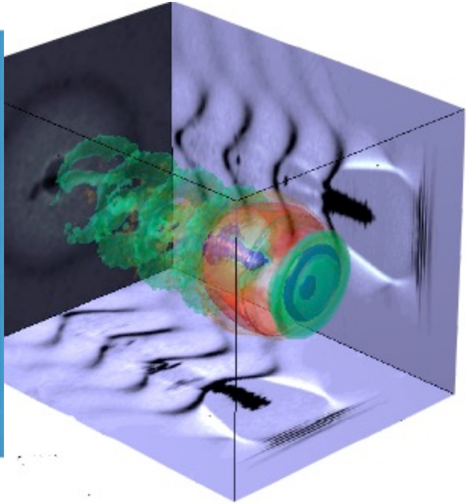


Surfing on an electric field

Laser Wakefield Acceleration (LWFA)

> 1000 papers since 2000 (Web of Science)

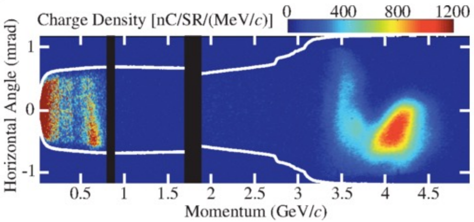
Experiments routinely demonstrate GeV electron beams from cm scale plasma i.e. 100 GeV/m acceleration gradients



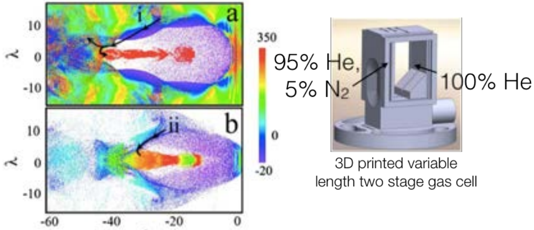
Electron beam properties

Quasi-monoenergetic

W Leemans, et al., PRL, 113, 245002 (2014)



100 pC charge



3D printed variable length two stage gas cell

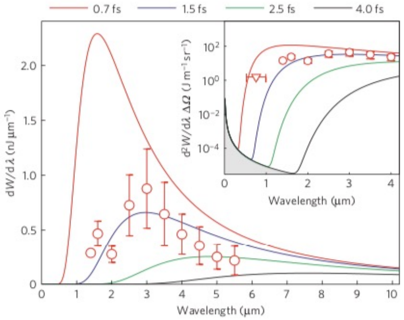
C McGuffey, et al., PRL, 104, 025004 (2010)

µm source size / small emittance

normalized rms beam transverse emittance $<0.5\pi$ mm mrad

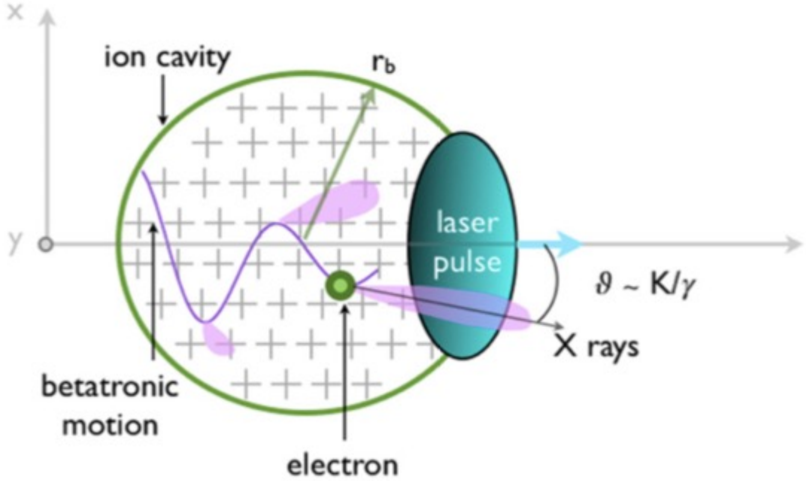
S Kneip, et al., PRSTAB, 15, 021302 (2012)

Femtosecond duration



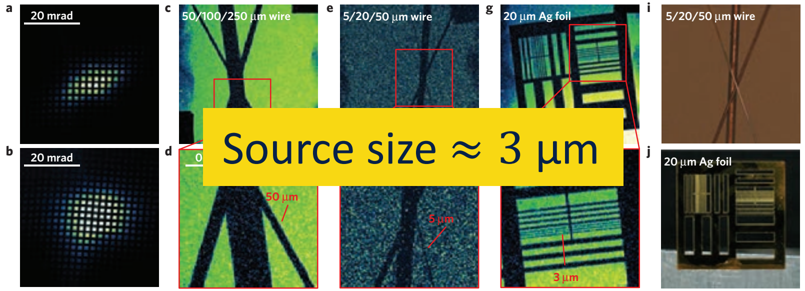
O Lundh, et al., Nature Physics, 7, 219 (2011)

"Bubbletron" or betatron radiation

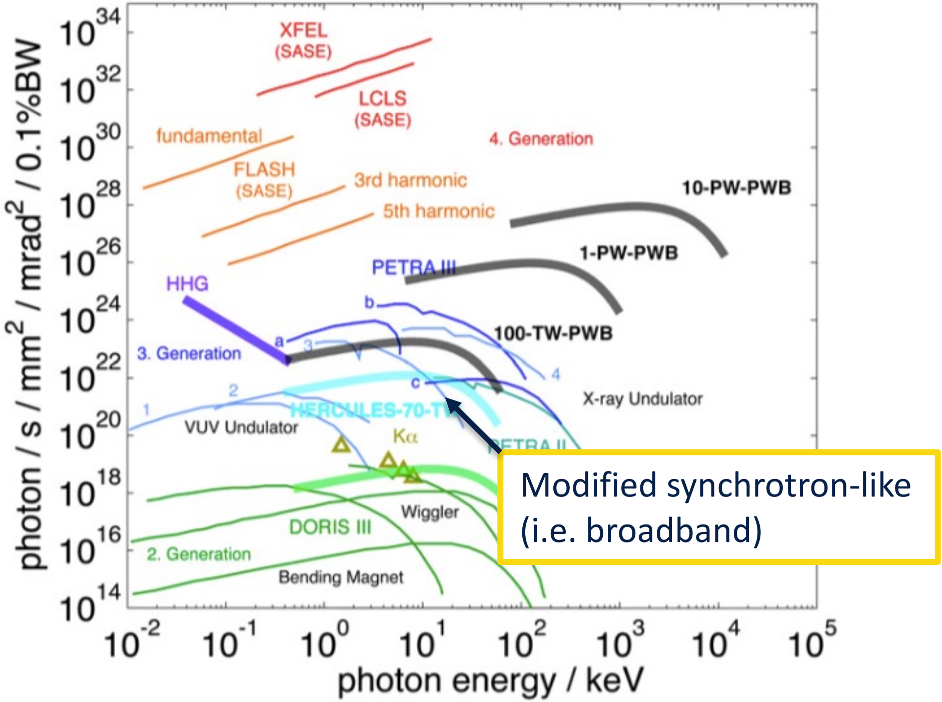


S Corde, et al, PPCF, 54, 124023 (2012)

S Kneip, et al, Nature Physics, 6, 980 (2010)

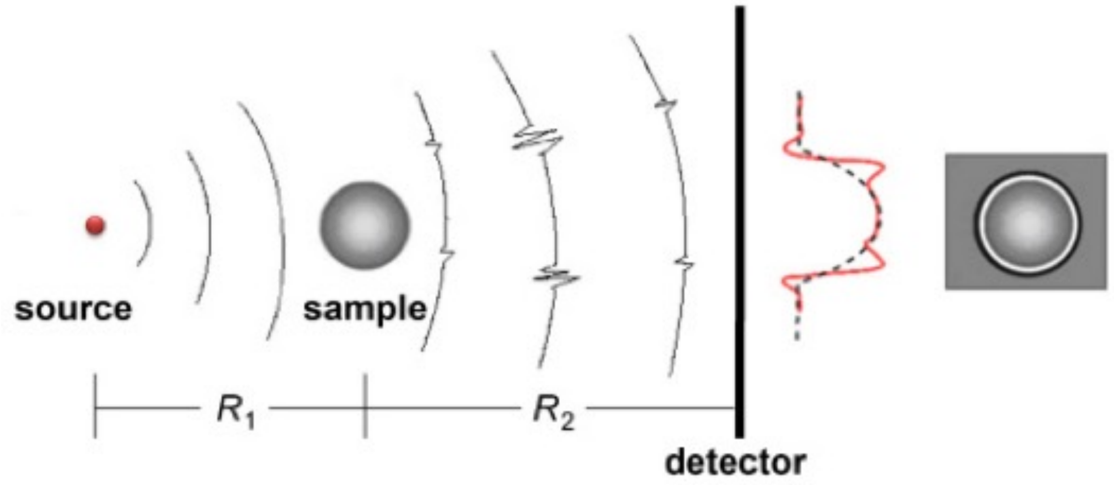


LWFA x-ray sources are as bright as conventional 3rd generation light sources



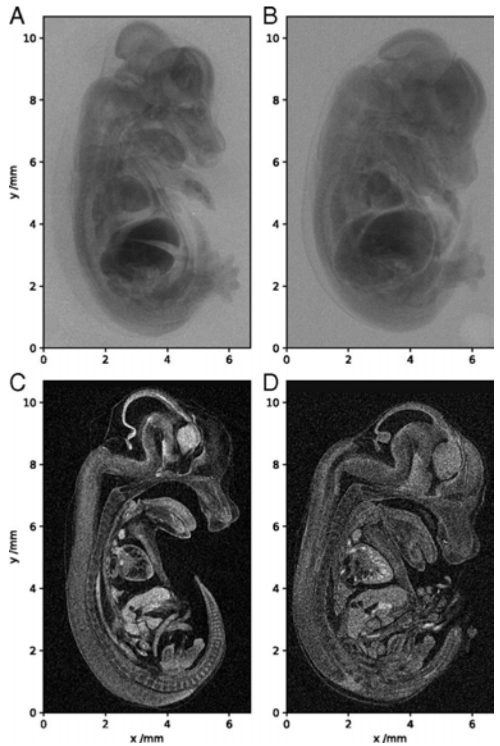
S Kneip, et al, HEDP, 8, 133 (2012)

Phase contrast imaging for medical applications



Commercial x-ray tube

LWFA-betatron

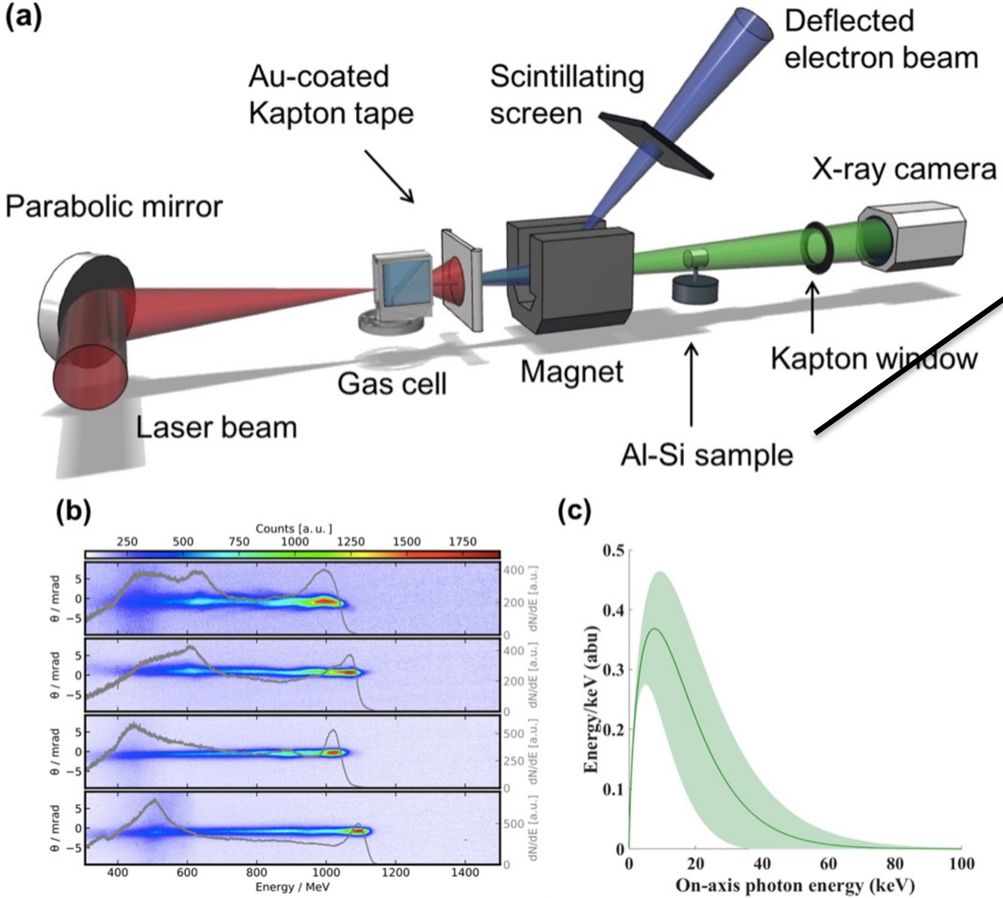


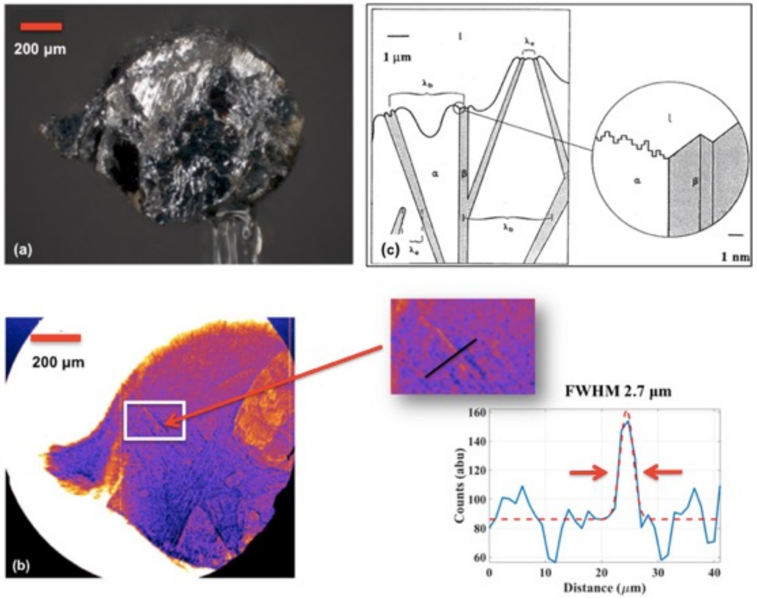
Small source allows propagation based phase contrast imaging

X-rays develop a degree of spatial coherence on propagation

JM Cole, et al, PNAS, 115, 6335 (2018)

Phase contrast imaging for material science





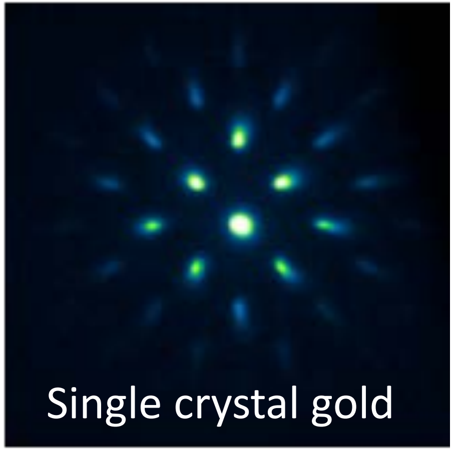
Imaging quality compares well with a synchrotron (Swiss light source)

AE Hussein, et al, Scientific Reports, 9, 3249 (2019)

Ultrafast probing (sub 100 fs)

(Inherently timed to laser for pump-probe applications)

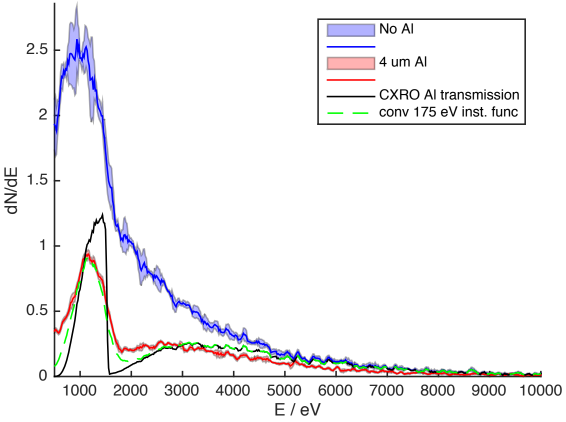
Visualization of global lattice dynamics and structural changes:
Electron or x-ray diffraction



Z-H He, et al, APL, 102, 064104 (2013)

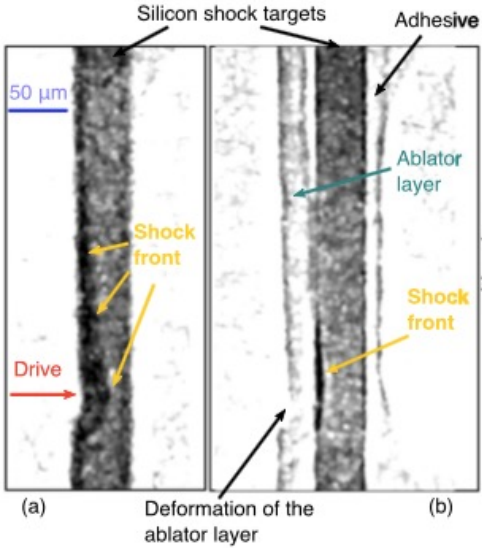
Kinetics of atomic transitions:

X-ray absorption spectroscopy



*K Behm, et al, High Energy Density Physics, **35**, 100729 (2020)*

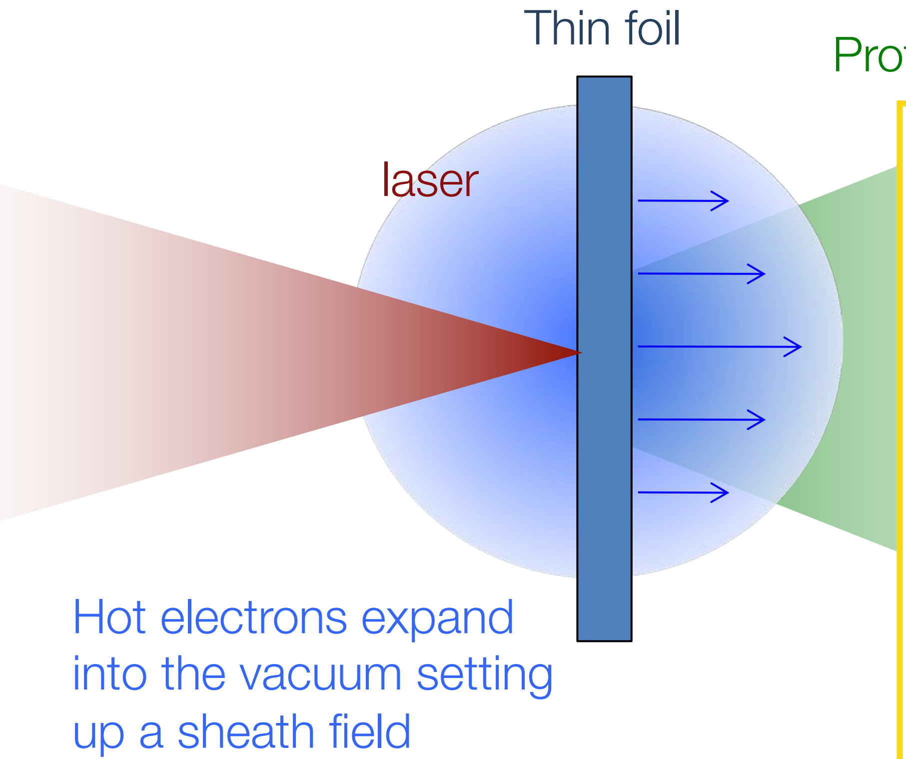
Dynamics of complex structures:
X-ray phase contrast imaging



JC Wood, et al, Scientific Reports, 8, 11010 (2018)

Target normal sheath acceleration (TNSA)

S Hatchett, et al, PoP, 7, 2076 (2000)



- ✓ Creates proton beams that are
  - Laminar (imaging quality ≥ 10 μm), transverse emittance < 0.004 mm mrad
  - short-duration (~picosecond at source)
  - high-flux proton beams ($>10^{12}$ protons)
- ✓ Mature theory and well studied mechanism
- ✓ Robust enough to explore applications

Energy conversion efficiency ~ few %

- ✗ Broad, Maxwellian-like energy spread (up to ~ 60MeV)
- ✗ Maximum ion energy scale with laser energy

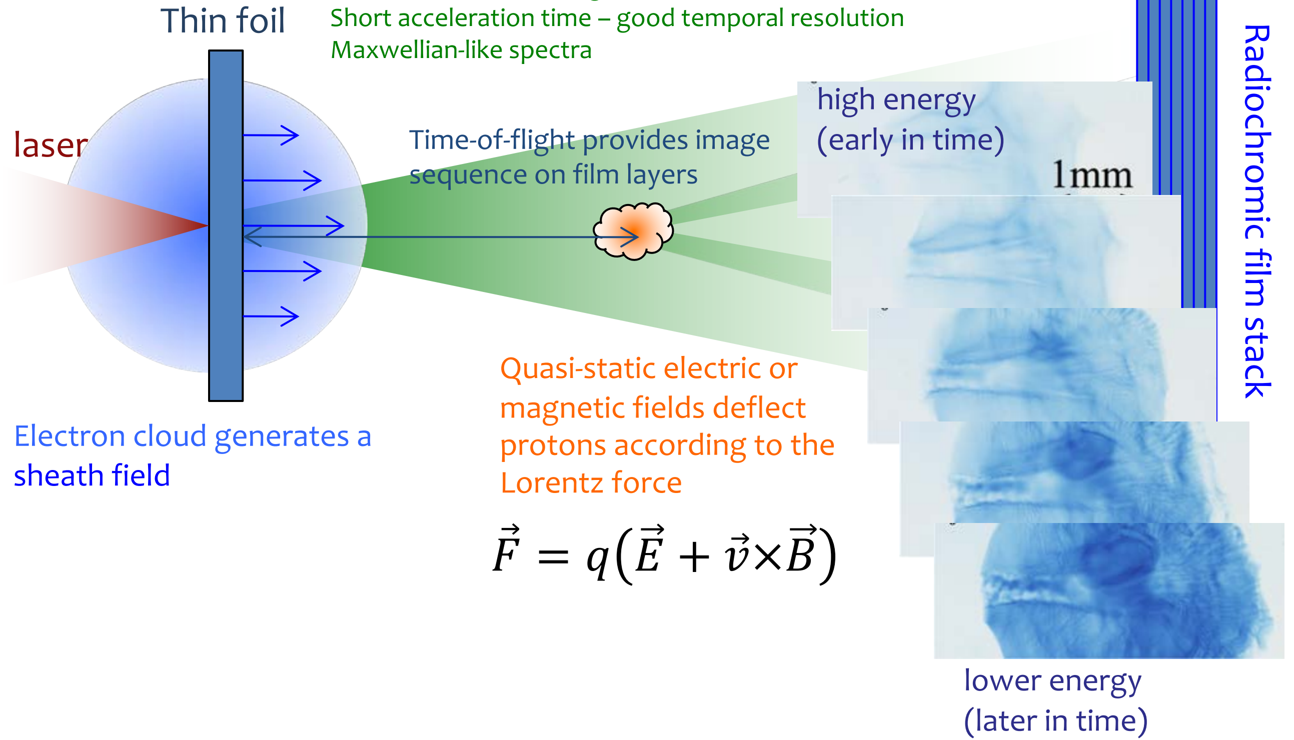
Application: Proton deflectometry

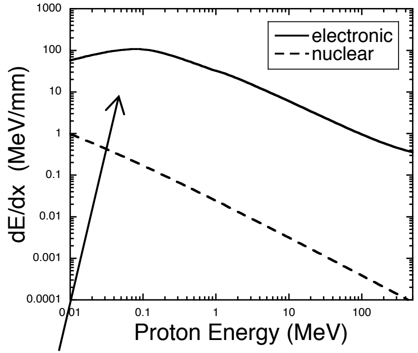
Proton beam is accelerated (via TNSA):

Laminar acceleration – good spatial resolution

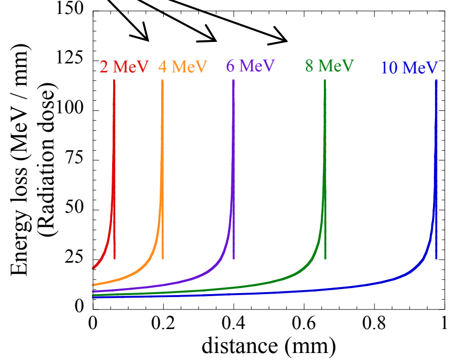
Short acceleration time – good temporal resolution

Maxwellian-like spectra





Bragg peak

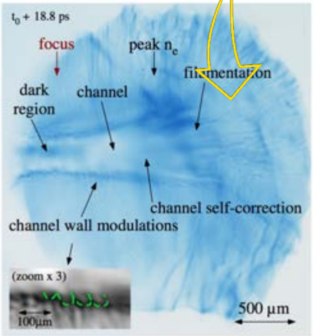


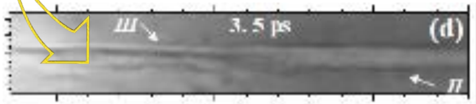
M Borghesi et al, Rev Sci Inst, 74, 1688 (2003); Laser and Part Beams, 20, 269 (2002)

Imaging electromagnetic fields with protons

Channel formation

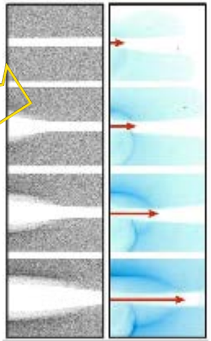
S Kar et al, NJP, 9, 402 (2007)
L Willingale, et al., PRL, 106, 105002 (2011)
L Willingale, et al., NJP, 15, 025023 (2013)

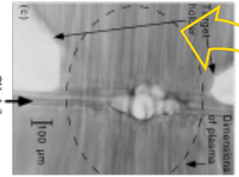




Ultrafast field propagation

K Quinn et al, PRL, 102, 194801 (2009)



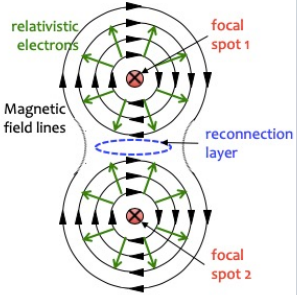


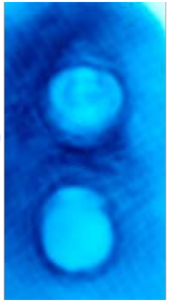
Soliton formation

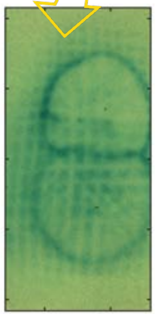
M Borghesi et al, PRL, 88, 135002 (2002)

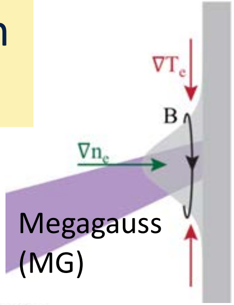
Magnetic reconnection

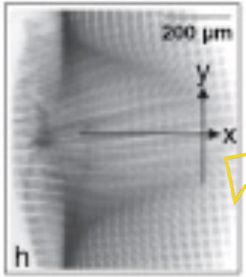
L Willingale et al, PoP, 17, 043104 (2010)
CAJ Palmer, et al., PoP, 26, 083109 (2019)





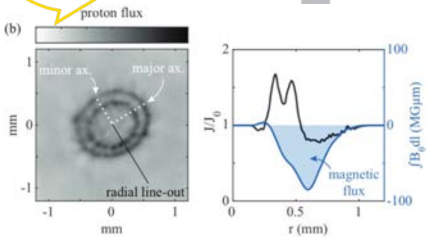






Magnetic field dynamics

P T Campbell, et al., PRL, 125, 145001 (2020)
P T Campbell, et al., in prep (2021)

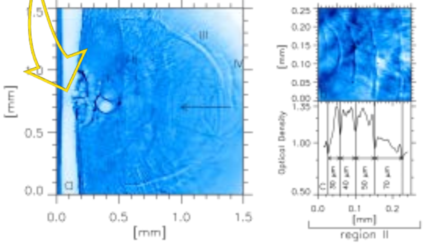


Proton Acceleration fields

L Romagnani et al, PRL, 95, 195001 (2008)

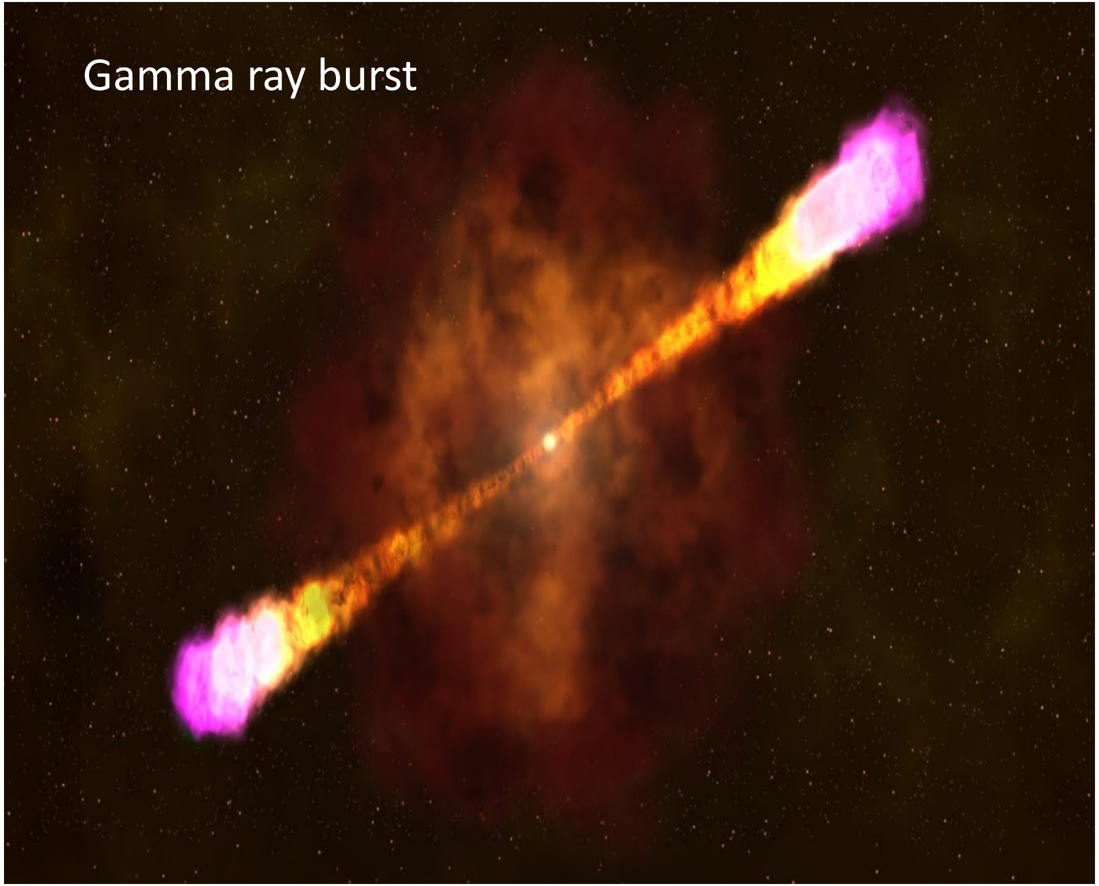
Collisionless shocks

L Romagnani et al, PRL, 101, 025004 (2008)

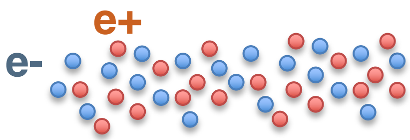


(this is a small subset of examples…)

Can we create a pair plasma in the laboratory?



Positrons have the same mass as electrons, but opposite charge.



The mass symmetry removes the separation of fast and slow scales present in electron-ion plasmas.

Tsytovich & Wharton (1978) Comments Plasma Phys. Controlled Fusion (1978)

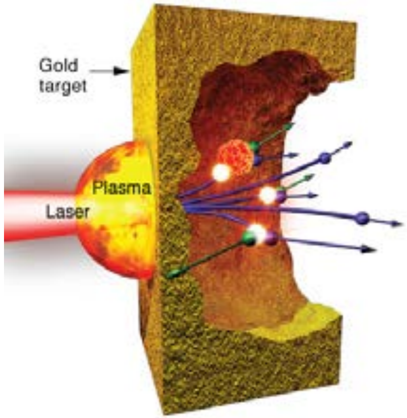
Collisionless shocks of relativistic pair plasma could be drivers of gamma emission.

Liang et al. Scientific Reports (2015) Sarri et al. Nature (2015)

Materials from Hui Chen (LLNL)

Pair plasma in the laboratory?

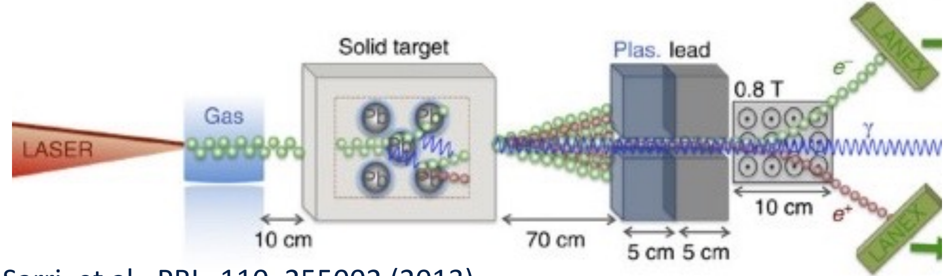
Laser plasma interactions can generate dense, relativistic energy electron beams



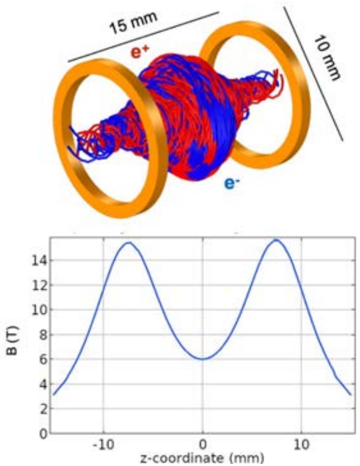
H Chen, et al., PRL, 102, 105001 (2009)

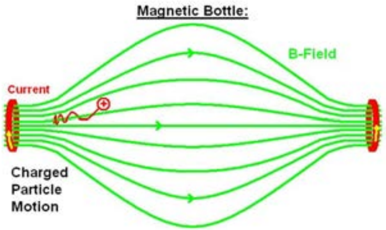
Require a large enough number of positrons for the system to be:

- Sufficiently dense
- Within a volume larger than the Debye length and skin depth
- For timescales longer than the phenomena of interest



G Sarri, et al., PRL, 110, 255002 (2013)





ZEUS

Zettawatt-Equivalent Ultrashort Pulse Laser System

ZEUS laser facility

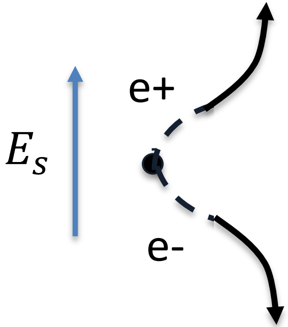
Zettawatt = 10^{21} W

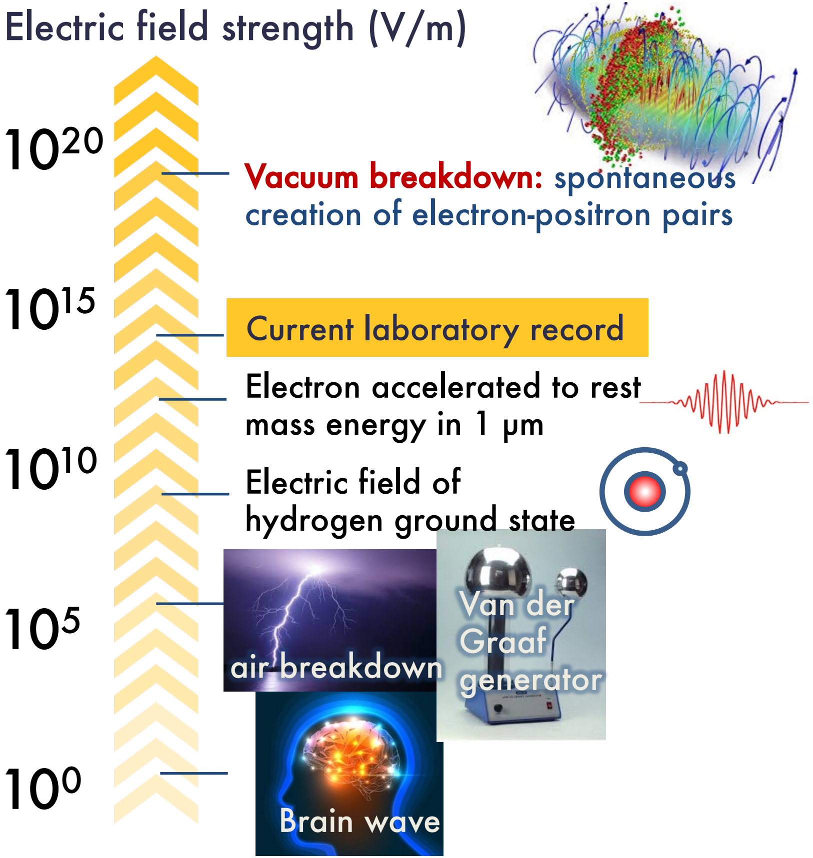
Equivalent

Critical field
$E_c \sim 10^{18}$ V/m

Ultrashort pulse laser

System





Zettawatt-Equivalent Ultrashort Pulse Laser System

ZEUS laser facility

Zettawatt $= 10^{21}$ W

Equivalent

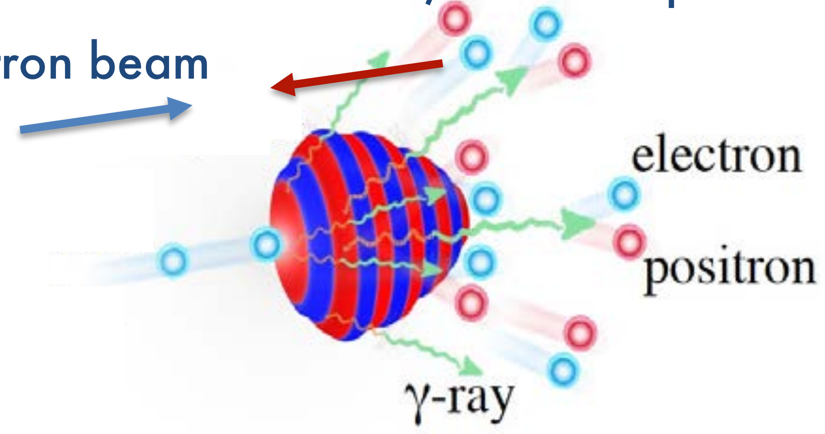
Critical field
$E_c \sim 10^{18}$ V/m

Ultrashort pulse laser

System

ZEUS power = 3 PW = 3 x 10^{15} W
(Highest power laser in the USA)

In the rest frame of reference, a GeV electron beam the intensity experienced will be equivalent to a Zettawatt power pulse!



User facility: due to be operational late 2023

QED in strong fields

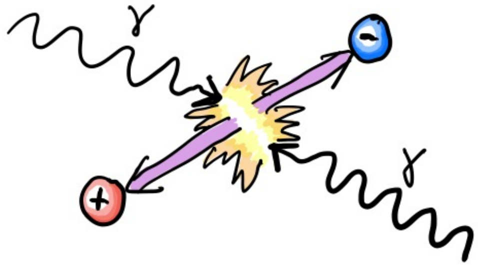
- We saw a relativistic plasma is generated above the classical nonlinear parameter threshold:

$$a = \frac{eE\lambda}{2\pi m_e c^2} = \frac{Quiver\ energy\ of\ electron}{m_e c^2}$$

- For electromagnetic fields exceeding the Quantum nonlinearity parameters, we can generate matter/anti-matter from light

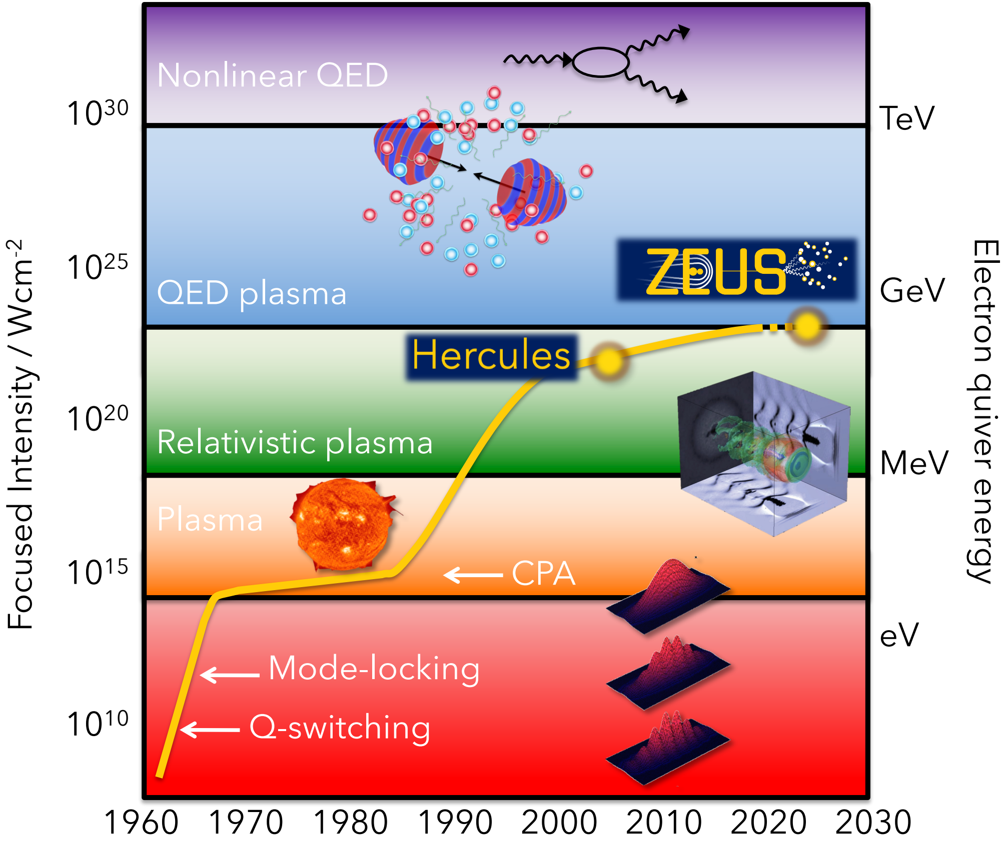
$$\chi_e = \frac{\|F_{\mu\nu}\upsilon^{\nu}\|}{E_c} = \frac{Amplitude\ of\ E\ in\ e\ rest\ frame}{E_c}$$

$$\chi_\gamma = \frac{\|F_{\mu\nu}\hbar k^{\nu}\|}{E_c} = \frac{Amplitude\ of\ E\ in\ e^+e^-\ center\ of\ mass}{E_c}$$



Artist: AGR Thomas

Creating QED-plasmas



$$\chi = 1$$

(lepton at rest)

Field strength boosted for energetic particles

$$\chi = 1$$

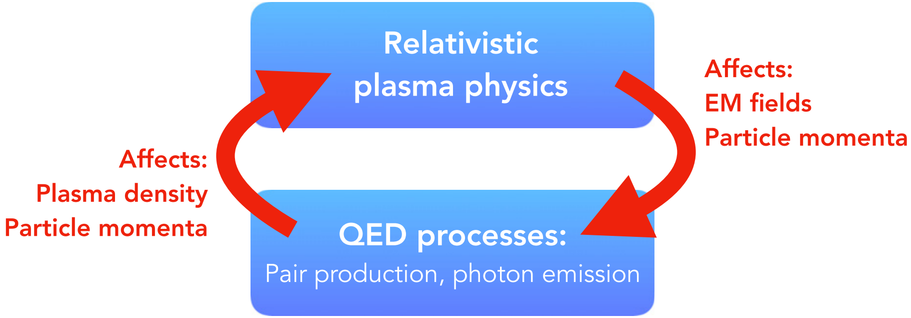
(lepton at energy $\sim a_0 m_e c^2$)

$$a_0 = 1$$

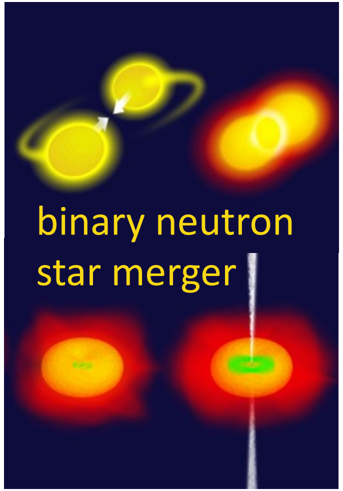
Extreme Plasma Physics

Extreme plasma physics is the area of many-body interactions in quantum electrodynamics – i.e. relativistic plasma interacting with electromagnetic fields.

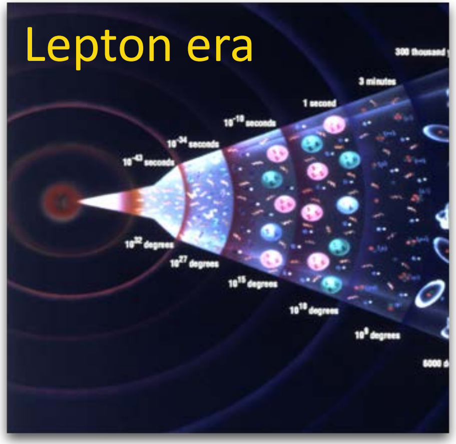
Coupling between QED processes and relativistic plasma physics introduces new behavior



P. Zhang et al, Phys. Plasmas (2020)

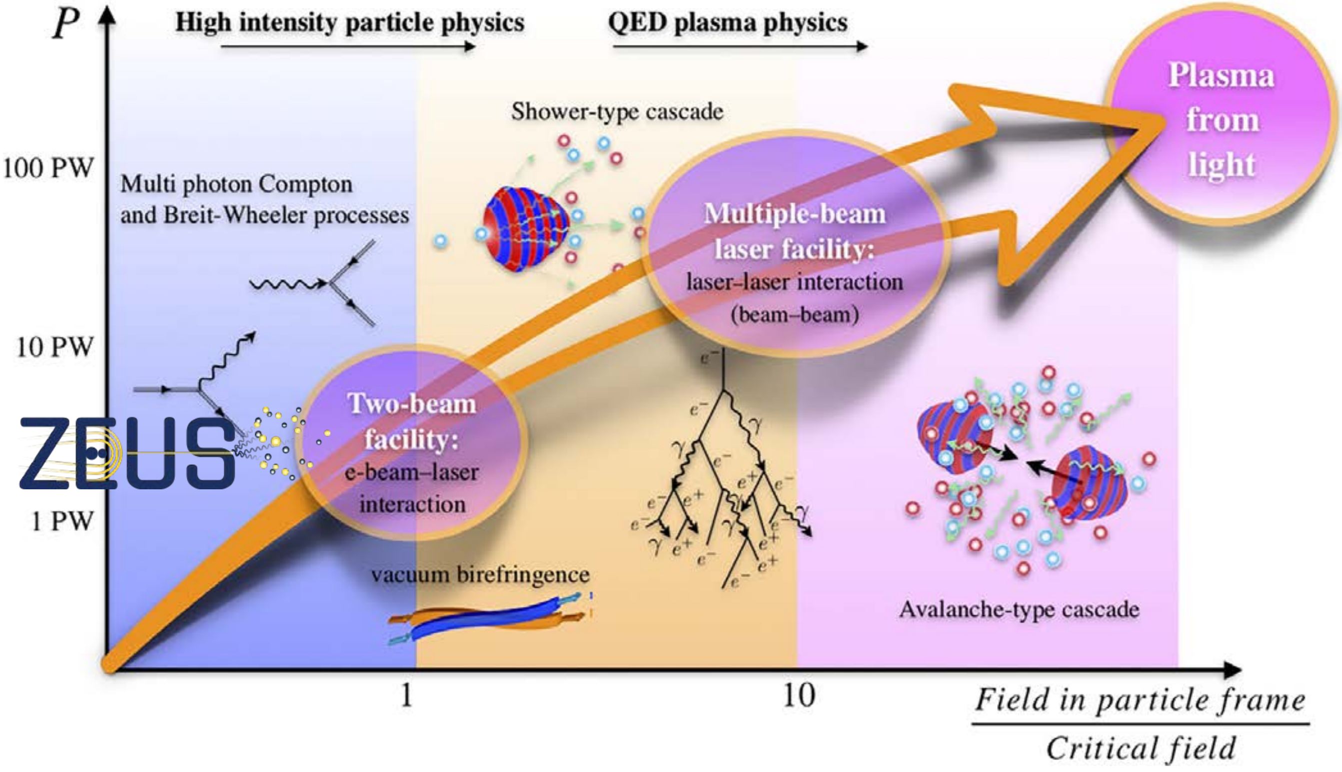


https://physics.aps.org/articles/v10/114



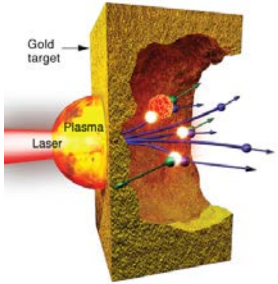
...After the first second, until the appearance of light nuclei (3 mins) is the lepton era - dominated by electron, positron, and photon plasma.

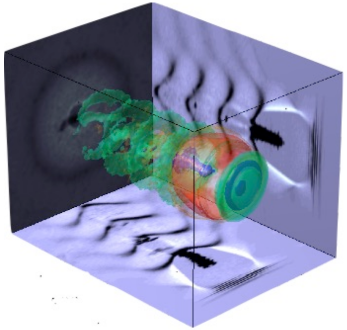
Multi-Petawatt lasers are the first step towards generating plasma from light



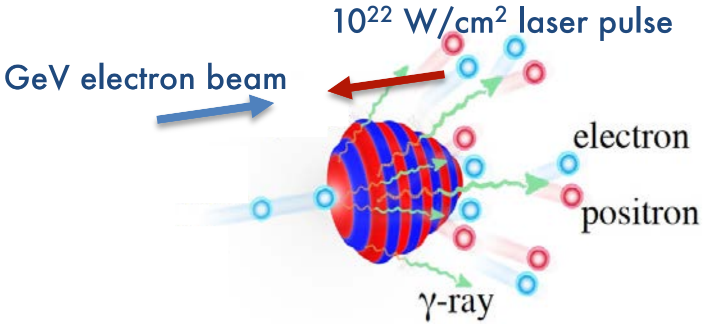
Workshop on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities (arXiv:1910.09084)

Short-Pulse Driven Relativistic Plasmas

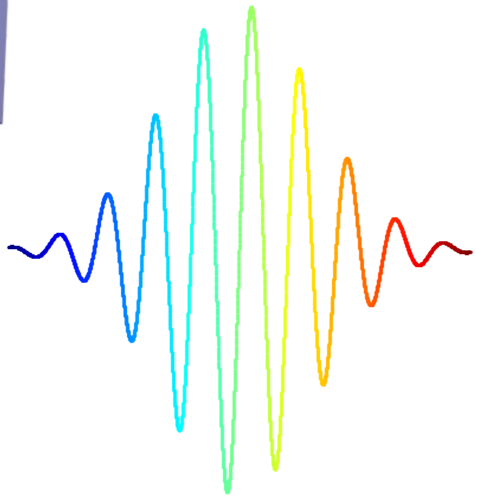




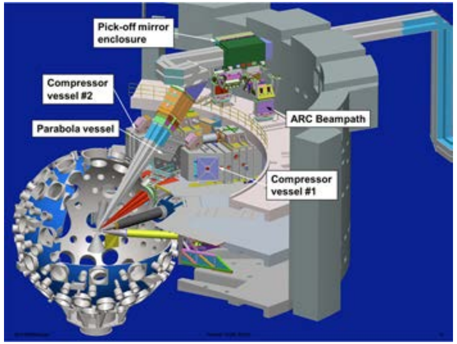
Laser pulse

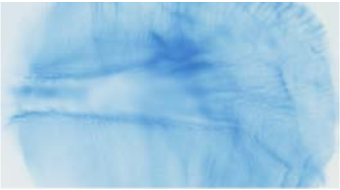


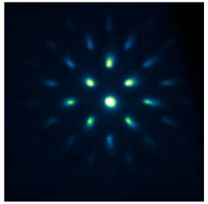
Compact particle accelerators and light sources

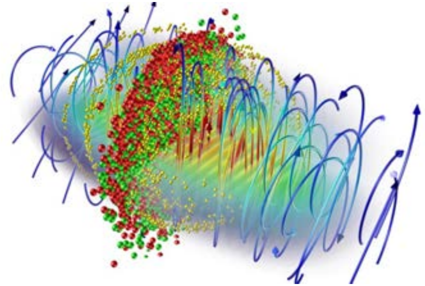


Extreme Plasma Physics / QED-plasmas









Michigan Institute for Plasma Science and Engineering

A collaborative support organization for research, education and industrial interactions for plasma science and engineering

- **Focal point for university wide activities in plasmas and interactions with Federal agencies.**
- Opportunities for collaborative research across departments.
- Seed research activities to attract center-level funding.
- **Enhance graduate education in PSE.**
- Facilitate research with industry.
- Outreach to broader community.
- Discipline resource for career opportunities.

Director: Prof Mark Kushner

69+ faculty members from UM, MSU and more…

Activities

- **Seminar Series (also webcast)**
- Graduate Symposium
- **Graduate Certificate**
- Job Opportunities
- Outreach activities
- Plasmas in our Lives (video interviews of seminar speakers)
- Entry point for industrial interactions – many opportunities for engagement
- mipse-central@umich.edu

Plasmas in our lives:

https://mipse.umich.edu/life_overview.php

>60 Short intro videos of the MIPSE seminar speakers

- Top researchers from around the world
- Wide range of plasma topics

MICHIGAN ENGINEERING
UNIVERSITY OF MICHIGAN